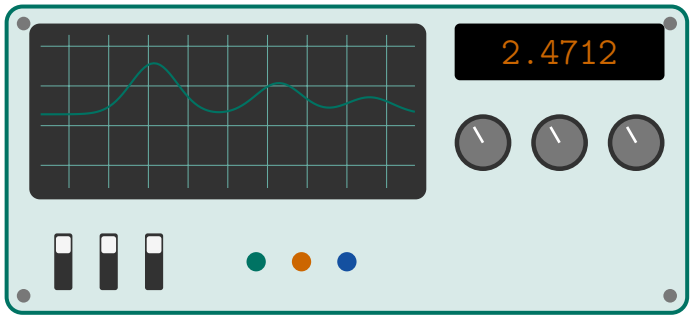
MZUZU UNIVERSITY

Faculty of Science, Technology & Innovation

Department of Physics & Electronics



Simulation Laboratory Manual

PHYS 4801

Fundamentals of Solid State Physics

Level 4 · Bachelor of Education (Science) / BSc Physics

Academic Year 2025/2026

Ten simulated laboratory benches, each modelled on real apparatus.
No programming, no installation — everything runs in a web browser.

Preface

This manual accompanies **PHYS 4801: Fundamentals of Solid State Physics** at Mzuzu University. It is written for **Education students** preparing to teach science.

Instead of a room full of hardware, this laboratory is a set of **ten simulated benches** that run in a web browser. Each bench is modelled on apparatus a solid state laboratory would really hold: a diffractometer with an X-ray tube and a shutter interlock; an adiabatic calorimeter with a heater and a thermometer; a semiconductor curve tracer; an electromagnet and a Hall probe; a cryostat with liquid nitrogen in the dewar. You set the controls, wait for the meters to settle, and write the readings down.

The instruments behave the way instruments do. Detector counts carry Poisson noise. Meter needles swing past a reading before settling on it. The Hall contacts are not exactly opposite one another, so there is an offset you have to remove. A cryostat filled with liquid nitrogen will not cool a lead sample below 77 K, no matter what setpoint you dial in. Learning to work around those things is part of the point.

Your job at every bench is the same four steps:

- **Set up** the apparatus using the control panel.
- **Observe** what the instruments do as you change a parameter.
- **Record** each measurement in the on-screen lab notebook.
- **Analyse** the exported data and answer the questions in this manual.

The physics follows the course text (Kittel, *Introduction to Solid State Physics*, 8th edition), and is computed from first principles wherever it reasonably can be: the Debye integral, the Bloch-Grüneisen resistivity, the Kronig-Penney condition and the X-ray structure factors are all evaluated numerically, not sketched.

Department of Physics & Electronics, Mzuzu University

Getting Started at the Bench

What you need

- A computer, laptop or tablet with a modern browser: Chrome, Firefox, Edge or Safari.
- WebGL enabled — the crystal stage at Bench 1 and the cryostat at Bench 9 are three-dimensional.
- An internet connection, or access to the copy hosted on the university laboratory network.
- **No** Python, **no** installation and **no** programming.

Finding your way around

When the platform opens you are standing on the **laboratory floor**: a card for each of the ten benches, with its station number, the apparatus it holds, and a small lamp that lights once you have used it.

Down the left-hand side is the **equipment rack**, the list of all ten benches. It collapses with the arrow at its top if you want more room. Below the ten stations it also links to the **Lab Notebook** and to an on-screen copy of this guide.

Every bench page is laid out the same way:

- a **placard** at the top with the experiment number, the apparatus, the duration and the Kittel chapter;
- the **apparatus** down the middle — the goniometer, the cryostat, the chart recorder, the meters;
- the **control panel** on the right, where every knob and switch lives;
- the **procedure card** and the **lab notebook** underneath;
- the **worksheet** of analysis questions at the very bottom.

Using the controls

The controls are modelled on real panel hardware, so they behave like hardware rather than like web sliders.

Control	How to use it
Rotary knob	Drag **up** or **right** to increase, **down** or **left** to decrease. Hold **Shift** while dragging for a fine vernier — you will need it. The scroll wheel nudges it. Once it has focus, the arrow keys step it one graduation at a time and Home/End jump to the ends of the range.
Slide fader	Drag the machined cap along its slot. The lit part of the track shows how far it is advanced.
Toggle switch	Click to throw the lever. The legend above it lights when the switch is ON.
Rotary selector	Click a position legend around the dial to jump straight to it, click the dial body to advance one position, or use the arrow keys.
Push button	Momentary — it travels and clicks. Buttons that latch stay lit while they are active.
Digital panel meter	Seven-segment readout of a measured quantity. A small flag lights in the corner for over-range, over-current, or when a reading is below the noise floor.
Moving-coil meter	The needle swings and settles like a real galvanometer. Let it come to rest before writing a reading down.
Scope screen	The phosphor display carrying the trace.
Indicator lamp	Green means ready or in range; amber means standby or caution; red means fault, over-range or interlock.

Note

Several instruments have **interlocks**, exactly as the real ones do. The X-ray shutter at Bench 2 will not open until the tube high voltage is on. The cryostat at Bench 9 will not go below the boiling point of whatever coolant is in the dewar. If a control refuses to move, read the message under it.

The lab notebook

Every bench has a notebook page at the bottom of it.

1. Open **Lab Notebook** from the rack **before you start** and enter your name, student number and group. Every export is stamped with them.
2. At each measurement point, set the controls, wait for the meters to settle, then press **Record reading**. The instrument readings are written into the table.
3. Delete a bad reading with the bin icon at the end of its row.
4. At the end of the session press **CSV** to download the table, and attach it to your written report.

Readings are stored **in your browser**, not on a server. They survive closing the tab, so a three-hour practical can be done over two sittings — but they are lost if you clear

your browsing data or move to another computer. **Export the CSV every session.**

Bench lighting and accessibility

The switch at the top right of every page has three positions:

Position	Effect
Up	Daylight laboratory: pale anodised panels, bright room.
Down	Night bench: gunmetal panels, dark room. Easier on the eyes for long sessions.
Auto	Follows whatever your computer or phone is set to.

Choosing **Up** or **Down** *overrides* your device setting, and the choice is remembered on that computer. Instrument screens stay dark in both positions, exactly as an oscilloscope screen does under bright room lights.

The speaker button beside it mutes the mechanical feedback from the controls.

Every control can be driven from the keyboard: **Tab** moves between them, the arrow keys adjust knobs, faders and selectors, and meters and readouts announce their values to screen readers.

Troubleshooting

Problem	What to do
Page does not load	Check the network connection, then refresh (F5).
3D stage is blank	The stage needs WebGL. Enable hardware acceleration in your browser, or try Chrome, Edge or Firefox.
Instrument will not start	Check the interlocks. Read the message under the control that is refusing.
A knob is too coarse	Hold **Shift** while dragging, or give it focus and use the arrow keys.
Controls feel slow	Close other browser tabs, or collapse the equipment rack.
Notebook is empty after coming back	Readings live in that browser only. Export the CSV every session.
Laboratory is too bright or too dark	Use the three-position bench-lighting switch at the top right.

Assessment and Report Writing

How this laboratory is assessed

Simulation laboratory work contributes to the **40%** Continuous Assessment component of PHYS 4801.

Component	Marks
Pre-simulation quiz / preparation	10%
In-lab observation and data recording	30%
Written simulation report	50%
Post-lab discussion	10%

Report structure

Your report for each experiment must contain:

1. **Title and details** — experiment number, your name, student number, date.
2. **Aim** — what the apparatus models and what you set out to investigate.
3. **Theory** — the key concepts and equations, in your own words.
4. **Observations** — your exported tables, with units and an estimate of the reading uncertainty.
5. **Analysis** — answers to the analysis questions, with graphs where the manual asks for them.
6. **Discussion** — what the measurement shows, and where the simulation departs from real apparatus.
7. **Conclusion** — two to four sentences summarising what you found.

Note

Quote uncertainties. Where the manual asks for a gradient, use a least-squares fit rather than a ruler through two points. Bench 8 reports the fit and its standard error for you; do the same by hand elsewhere.

Contents

CHAPTER 1

Experiment 1: Exploring Crystal Structures

Apparatus: Crystallographic Model Stage (Bench 1)

Duration: 3 hours
Topics: Crystal lattice, unit cell, basis, Bravais lattices, APF, coordination number
Kittel: Chapter 1
Asset tag: MZU-PE / GON-1

Student Name:		**Date:**	
Student Number:		**Group:**	

1.1 Learning Objectives

Learning Objectives

1. Mount and index the unit cells of SC, BCC, FCC, rock salt and diamond on the model stage.
2. Measure the packing fraction of each structure by bringing the atomic spheres into contact.
3. Relate crystal structure to density, ductility and hardness.
4. Understand the idea of lattice + basis.
5. Identify the structure of common materials from their cell parameters.

1.2 Background Theory

Key Equations

A crystal structure is a **Bravais lattice** plus a **basis**. The unit cell is the smallest volume that repeats to fill space. Two numbers describe how efficiently it is filled:

$$\text{APF} = \frac{n \cdot \frac{4}{3}\pi r^3}{a^3}, \qquad \text{CN} = \text{number of nearest neighbours.}$$

The APF is only meaningful when the spheres are *just touching*. The contact

conditions are

$$\text{SC: } 2r = a, \quad \text{BCC: } 4r = a\sqrt{3}, \quad \text{FCC: } 4r = a\sqrt{2}, \quad \text{diamond: } 8r = a\sqrt{3}.$$

The density follows from the cell contents:

$$\rho = \frac{n\, M_r}{N_A\, a^3}.$$

1.3 At the Bench

Bench 1 — Crystallographic Model Stage

Open **Bench 1** from the equipment rack.

▶ At the bench

The apparatus is a **goniometer stage** inside a lit viewing chamber, with a five-position **sample carousel** beside it.

- **Viewing chamber** (centre): the mounted specimen in 3D. Drag to rotate the stage, scroll to zoom. Blue spheres are the corner or A-type atoms; orange are the additional basis atoms.
- **Cell metrology** (below): digital readouts for atoms per cell, coordination number, sphere radius r/a, the fraction of cell volume filled, the lattice parameter and the density.
- **Model stage control** (right): the **Sample carousel** dial, the **Radius** r/a knob, the four **Index along** buttons ([100], [110], [111], Free), and toggles for **Cell edges**, **Bonds** and **Spin**.

Two lamps matter throughout: **Contact** lights when the spheres are just touching, and **Overlap** lights red once you have wound the radius past that point and the spheres are interpenetrating.

1.4 Guided Observations

Task: A — Compare all five structures

Turn the sample carousel through SC, BCC, FCC, NaCl and diamond in turn. For each structure, wind the **Radius** r/a knob up slowly until the **Contact** lamp lights — hold **Shift** for the fine vernier — and record the readings in Table 1.1. The **volume filled** readout is the packing fraction *only* at contact. That is what the lamp is for.

Table 1.1: Crystal structure properties measured on the model stage.

Structure	n	**CN**	r/a	**APF**	a **(Å)**	**Specimen**
Simple cubic						
BCC						
FCC						
Rock salt (NaCl)						
Diamond cubic						

Task: B — Index the FCC cell

Load **FCC** (the specimen is copper) and switch **Spin** off so the stage holds still.

a) Press the **[111]** index button. Looking straight down the body diagonal, what shape do the face-centre atoms form?

_____

b) Press **[100]**. Looking down the z-axis, how many atoms can you see on the square face?

_____

c) Press **[110]**. Describe what happens to the apparent spacing of the planes.

_____

Task: C — Verify the BCC packing factor

Load **BCC** (iron) and find the contact radius on the stage: $r/a =$_____. Check it against $4r = a\sqrt{3}$, then compute the packing factor by hand and compare with the readout:

$$\mathrm{APF}_{\mathrm{BCC}} = \frac{2 \cdot \frac{4}{3}\pi \left(\frac{a\sqrt{3}}{4}\right)^3}{a^3} = \underline{\qquad\qquad}$$ Stage reading: _____

Show your working:

Task: D — Rock salt and diamond

Switch to **NaCl**.

a) Two ion sizes are visible. Which colour is the smaller Na^+ ion?

_____

b) How many nearest neighbours does each ion have, and of which kind?

c) The stage holds the ionic radius ratio fixed at $r(\mathrm{Na}^+)/r(\mathrm{Cl}^-) = 0.56$. What packing fraction do you measure at contact, and why is it not the 0.52 you would get from equal spheres?

Now load **Diamond** (silicon) and switch **Bonds** on.

d) The coordination number is only 4 and the packing fraction only 0.34. Why is diamond nevertheless the hardest material you will meet?

1.5 Analysis Questions

1. From your table, which structure has the highest packing fraction and which the lowest? What does a higher packing fraction tell you about how efficiently the atoms fill space?

2. FCC has CN = 12 while SC has CN = 6. How does coordination number relate to the ductility of a metal? Copper (FCC) is very ductile, tungsten (BCC) is more brittle — explain that trend.

3. Silicon has the diamond structure with CN = 4 and is a semiconductor; copper is FCC with CN = 12 and is a metal. What does the coordination number alone tell you about the type of bonding?

4. The stage measured a packing fraction of about 0.65 for rock salt at contact, but forcing both ions to the same size gives 0.52. Why does the radius ratio matter so much?

Physics Problems

1. A metal crystallises FCC with $a = 3.61\,\text{Å}$ and a density of $8960\,\text{kg m}^{-3}$. Identify it using $\rho = nM_r/(N_A a^3)$, then check your answer against the density readout for copper.
2. Explain what the *basis* is in the rock salt structure, and why NaCl is described as two interpenetrating FCC lattices.
3. In diamond each atom forms four covalent bonds. Switch the bonds on and describe how that tetrahedral geometry follows from the $(\tfrac{1}{4},\tfrac{1}{4},\tfrac{1}{4})$ displacement of the second atom in the basis.
4. Why does the stage draw the BCC body-centre atom in a different colour from the corner atoms, even though every atom in pure iron is chemically identical?

CHAPTER 2

Experiment 2: X-ray Bragg Diffraction

Apparatus: θ–2θ Powder Diffractometer (Bench 2)

Duration: 3 hours
Topics: Bragg's law, X-ray diffraction, structure factors, systematic absences, powder met
Kittel: Chapter 2
Asset tag: MZU-PE / XRD-2

Student Name:		**Date:**	
Student Number:		**Group:**	

2.1 Learning Objectives

Learning Objectives

1. Bring up an X-ray tube safely and run a θ–2θ powder scan.
2. Locate and index the Bragg reflections of a cubic powder.
3. Verify Bragg's law $2d\sin\theta = n\lambda$ from your own measurements.
4. Observe how changing the tube changes which reflections are accessible.
5. Recognise systematic absences and relate them to the structure factor.

2.2 Background Theory

Key Equations

Bragg's law:

$$2d_{hkl}\sin\theta = n\lambda, \qquad n = 1, 2, 3, \ldots$$

where θ is the glancing angle between the beam and the planes. Diffraction is impossible unless $\lambda \leq 2d$.

For a cubic lattice,

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}.$$

Not every (hkl) appears. The structure factor removes some entirely:

BCC	only $h + k + l$ even
FCC	only h, k, l all even or all odd
Diamond	the FCC rule, *and* all-even reflections need $h + k + l = 4n$
Rock salt	the FCC rule; all-odd reflections are weak because $f_{\mathrm{Cl}} - f_{\mathrm{Na}}$ is small

2.3 At the Bench

Bench 2 — θ–2θ Powder Diffractometer

Open **Bench 2** from the equipment rack.

▶ At the bench

The apparatus is drawn in plan view: a fixed **X-ray tube** on the left, the **specimen** on a rotating stage at the centre of the goniometer circle, and the **detector** on an arm. As the detector is driven to 2θ, the specimen turns to θ, so its face always bisects the two beams.

- **Goniometer** (top): the beam is only drawn when the tube high voltage is on *and* the shutter is open. The radiation trefoil in the corner lights whenever X-rays are out.
- **Chart recorder** (middle): the diffractogram. **Start scan** sweeps the detector from 10° to 140° and the pen draws counts against 2θ as it goes. **Peak search** drives the goniometer onto the nearest reflection. The **hkl** toggle labels the allowed reflections on the trace.
- **Detector electronics** (below): 2θ, θ, count rate, $\sin\theta$, the wavelength of the fitted tube, and the d-spacing the instrument reports from Bragg's law. The **PK** flag lights when you are sitting on a peak.
- **Control panel** (right): the **Tube HV** and **Shutter** switches, the **Anode** dial (Cu, Co, Cr, Mo), **Voltage** and **Current** knobs, the **Sample rack** dial, **Specimen temp** and **Count time** knobs, and the **Detector angle** 2θ drive.

Note

The shutter is interlocked: it will not open until the tube high voltage is on. This is exactly how a real diffractometer is wired. The count rate carries Poisson noise, so a longer count time gives a smoother trace at the cost of a slower scan.

2.4 Guided Observations

Task: A — Bring the beam up and take a scan

Fit the **Cu** anode, load the **NaCl** powder, and set 40 kV and 30 mA. Switch **Tube HV** on, then open the **Shutter**, then press **Start scan**. Let the pen run to 140°.
Sketch the diffractogram, or list the approximate 2θ of every peak you can see:

Task: B — Index the reflections

Drive the **Detector angle** knob to each peak in turn and press **Peak search** to sit exactly on it. Wait for the ratemeter to settle, then record the reading. Switch the **hkl** labels on only after you have made your own attempt at indexing.

Table 2.1: Bragg reflections of NaCl with Cu Kα, $\lambda = 1.5406$ Å.

(hkl)	2θ (°)	θ (°)	$\sin\theta$	d **from Bragg (Å)**	$a/\sqrt{h^2+k^2+l^2}$ **(Å)**

Task: C — Change the wavelength

Keep the NaCl specimen and swap the anode.

a) Fit **Mo** ($\lambda = 0.7107$ Å) and rescan. What happens to the whole pattern, and why?

_____

b) Fit **Cr** ($\lambda = 2.2897$ Å) and rescan. Which reflections have disappeared?

_____

c) Diffraction requires $\lambda \le 2d$. For the reflection that vanished, what is $2d$? $2d =$ _____ Å.

d) X-rays have $\lambda \approx 0.05$–2.5 Å. Why does that range make them uniquely suited to crystal diffraction, when visible light ($\lambda \approx 5000$ Å) is useless?

Task: D — Absences, glass and temperature

Refit the Cu anode.

a) Scan **Fe** (BCC) and **Al** (FCC). Switch on the **hkl** labels and list the reflections that appear for each. What rule is each obeying?

b) Scan **Si** (diamond cubic). Which two reflections are missing that the FCC rule alone would have allowed? _____

c) Scan **SiO_2**, the fused silica. Describe how the trace differs from a crystalline one, and say what that tells you about the atomic arrangement.

d) Reload NaCl and take the **Specimen temp** knob from 100 K to 900 K, rescanning at each end. Record the shift of one peak and what happens to the high-angle peak heights.

2.5 Analysis Questions

1. Plot $\sin\theta$ against $1/d$ for the reflections you indexed in Task B. What is the gradient, and what physical quantity is it?

2. Compare the Fe and Al scans. Iron is missing every reflection with $h + k + l$ odd; aluminium is missing every mixed-parity reflection. Explain both, thinking about a plane of atoms halfway between the ones you are indexing.

3. Silicon is missing (200) and (222) even though both satisfy the FCC rule. What does that tell you about the second atom in the diamond basis?

4. When you heated the NaCl specimen the peaks moved to lower 2θ *and* the high-

angle ones lost height. Account for both effects separately.

Physics Problems

1. Aluminium is FCC with $a = 4.05\,\text{Å}$. Calculate d_{111} and the Bragg angle for the (111) reflection with Cu Kα, then check both on the instrument.
2. Neutrons of wavelength $1.80\,\text{Å}$ can be used instead of X-rays. What extra information do they give? Consider magnetic as well as nuclear scattering.
3. A crystal expands by 0.5% on heating. Use $2d\sin\theta = \lambda$ to estimate the shift, in degrees, of a peak that sat at $2\theta = 45^\circ$.
4. Describe in plain language what the Ewald sphere represents, and state the condition under which a reciprocal lattice point lies on it.

CHAPTER 3

Experiment 3: Phonons and Lattice Heat Capacity

Apparatus: Lattice Dynamics Rig and Adiabatic Calorimeter (Bench 3)

Duration: 3 hours
Topics: Lattice vibrations, phonons, dispersion, Dulong-Petit, Einstein and Debye models
Kittel: Chapters 4 & 5
Asset tag: MZU-PE / CAL-3

Student Name:		**Date:**	
Student Number:		**Group:**	

3.1 Learning Objectives

Learning Objectives

1. Drive a one-dimensional chain and see acoustic and optical modes as real motion.
2. Read the dispersion relation $\omega(k)$ and the group velocity across the Brillouin zone.
3. **Measure** a heat capacity by calorimetry: deposit a known energy and read the temperature rise.
4. Compare your measurements with the Dulong-Petit, Einstein and Debye models.
5. Explain why the classical model fails, and where.

3.2 Background Theory

Key Equations

For a monatomic chain of mass M and force constant C,

$$\omega = 2\sqrt{\frac{C}{M}}\left|\sin\left(\frac{ka}{2}\right)\right|.$$

A diatomic chain has two branches, acoustic and optical, separated by a fre-

quency gap at the zone boundary.

Molar heat capacities:

$$\text{Dulong-Petit:}\quad C_V = 3R = 24.94\ \mathrm{J\,mol^{-1}K^{-1}}$$

$$\text{Einstein:}\quad C_V = 3R\left(\frac{\Theta_E}{T}\right)^2 \frac{e^{\Theta_E/T}}{(e^{\Theta_E/T}-1)^2}$$

$$\text{Debye:}\quad C_V = 9R\left(\frac{T}{\Theta_D}\right)^3 \int_0^{\Theta_D/T} \frac{x^4 e^x}{(e^x-1)^2}\,dx \xrightarrow{T\ll\Theta_D} \frac{12\pi^4 R}{5}\left(\frac{T}{\Theta_D}\right)^3$$

The calorimeter measures $C = Q/(n\,\Delta T)$.

3.3 At the Bench

Bench 3 — Lattice Dynamics Rig and Calorimeter

Open **Bench 3** from the equipment rack.

▶ At the bench

This bench holds two instruments.

The lattice dynamics rig (top) is a ball-and-spring chain. The atoms are displaced *along* the chain, as they really are in a longitudinal lattice wave, and the springs visibly compress and stretch. A displacement profile u_n is traced underneath, and the wavelength is marked in units of the lattice constant.

Its controls are the **Wavevector** k knob, the **Chain type** switch (monatomic / diatomic), the **Branch** switch (acoustic / optical), and **Mass ratio** and **Play speed** knobs. **Freeze** stops the motion so you can study a snapshot. The **dispersion analyser** beside it plots ω against k with a cursor at your setting, and reads out the group velocity $d\omega/dk$.

The adiabatic calorimeter (right) holds a weighed specimen in a cryostat. Set the **Bath temperature**, choose a **Heater power** and a **Pulse length**, and press **Fire pulse**. The thermometer needle rises and settles, and the instrument reports ΔT and $C = Q/n\Delta T$.

The **heat capacity plotter** below draws the Debye, Einstein and Dulong-Petit curves for the loaded specimen. **Plot last point** adds your measurement to the same axes.

Note

A **HI** flag lights if ΔT exceeds about 8% of T. The heat capacity is not constant over an interval that large, so the number you get is an average over it rather than $C(T)$. Reduce the heater power or the pulse length until the flag goes out.

3.4 Guided Observations

Task: A — Modes of the monatomic chain

Start with the **monatomic** chain running. Set k to its minimum.

a) Describe the motion. How does the wavelength compare with the length of the rig?

_____

b) Wind k up to the zone boundary, $k = \pi/a$. What has happened to the wavelength?

_____

c) At the zone boundary, do adjacent atoms move in the same direction or in opposite directions?

_____

d) Read the group velocity $d\omega/dk$ at $k \to 0$ and at $k = \pi/a$: _____ and _____.

Task: B — Acoustic and optical branches

Switch to the **diatomic** chain with a mass ratio of about 0.5.

a) Two branches now appear. At small k, which branch has the two masses moving *together* and which has them moving *against* each other?

_____

b) Read the frequency gap at the zone boundary, then change the mass ratio to 0.9 and read it again. What happens as the two masses become equal, and why?

_____

c) At $k = 0$ on the optical branch the two masses vibrate exactly out of phase. In a polar crystal such as NaCl that motion is an oscillating electric dipole. Why does that make the branch "optical"?

_____

Task: C — Measure a heat capacity

Load **copper** in the calorimeter and set the bath to 300 K. Choose a heater power and pulse length that give a ΔT of a kelvin or so, fire the pulse, and record everything. Repeat at 200, 100, 50 and 20 K, reducing the pulse each time so the **HI** flag stays out.

Table 3.1: Calorimetry on copper, $\Theta_D = 343\,\mathrm{K}$.

T (K)	T/Θ_D	Q (J)	ΔT (K)	C (J mol^{-1}K^{-1})	$C/3R$	Debye C
300						
200						
100						
50						
20						

Task: D — Where the classical model fails

Repeat a single 300 K measurement on **diamond** ($\Theta_D = 2230\,\mathrm{K}$) and on **lead** ($\Theta_D = 105\,\mathrm{K}$).

a) Diamond: $C =$ _____ J mol^{-1}K^{-1}, i.e. $C/3R =$ _____.

b) Lead: $C =$ _____ J mol^{-1}K^{-1}, i.e. $C/3R =$ _____.

c) Dulong-Petit predicts $C/3R = 1$ for both. Which one obeys it at room temperature, and why?

_____

d) Diamond was the anomaly that broke the classical law. What did Einstein add in 1907 to fix it?

_____

3.5 Analysis Questions

1. Plot your measured C against T^3 for the four lowest copper points. Is it linear? What does the gradient give you?

2. The five specimens have Θ_D from 105 K to 2230 K, with molar masses Pb 207, Cu 63.5, Fe 55.8, Al 27.0, C 12.0 g mol^{-1}. Describe the trend and explain how Θ_D depends on atomic mass and bond stiffness.

3. At the zone boundary the group velocity fell to zero. What does that mean physically for a phonon with that wavevector?

4. Compare the Einstein and Debye curves at low temperature on the plotter. Which falls too quickly, and which assumption causes it?

Physics Problems

1. Using $\Theta_D(\mathrm{Cu}) = 343\,\mathrm{K}$, calculate $C_V/3R$ at $T = 10\,\mathrm{K}$ from the T^3 law and compare with the calorimeter.
2. Explain in physical terms what a phonon is, and why the idea is useful even though no atom travels through the crystal.
3. Why does the diatomic chain have a frequency gap between the branches? Argue from the restoring forces at the zone boundary.
4. Define the Debye temperature in terms of the maximum phonon frequency, and explain why a material with a large Θ_D stores less heat at room temperature.

CHAPTER 4

Experiment 4: Fermi-Dirac Statistics and the Free Electron Model

Apparatus: Electron Energy Analyser (Bench 4)

Duration: 3 hours
Topics: Quantum free electron model, Fermi-Dirac distribution, density of states, Fermi e
Kittel: Chapter 6
Asset tag: MZU-PE / EEA-4

Student Name:		**Date:**	
Student Number:		**Group:**	

4.1 Learning Objectives

Learning Objectives

1. Observe the Fermi-Dirac function and how temperature smears it.
2. Measure the width of the Fermi edge and use it to obtain Boltzmann's constant.
3. Relate the Fermi energy of a metal to its conduction electron density.
4. Compare a metal with a semiconductor, where a gap opens at E_F.
5. Understand why only electrons within $\sim k_B T$ of E_F matter.

4.2 Background Theory

Key Equations

The probability that a state of energy E is occupied is

$$f(E) = \frac{1}{e^{(E-E_F)/k_B T} + 1}.$$

At $T = 0$ this is a step; at finite T it smears over a width of order $k_B T$. Measured between the 90% and 10% points the width is exactly

$$W = 2k_B T \ln 9 = 4.394\, k_B T.$$

For a free electron gas of density n,

$$E_F = \frac{\hbar^2}{2m}\left(3\pi^2 n\right)^{2/3}, \qquad g(E) \propto \sqrt{E}.$$

Only a fraction $\sim k_B T/E_F$ of the electrons can be thermally excited, which is why the electronic heat capacity is so small.

4.3 At the Bench

Bench 4 — Electron Energy Analyser

Open **Bench 4** from the equipment rack.

▶ At the bench

The apparatus is an electron energy analyser looking at a sample in a helium cryostat. A slit selects one energy at a time, and a channeltron behind it counts the electrons that get through.

- **Occupation spectrum** (top): $f(E)$ in amber, the density of states $g(E)$ in blue, and the occupied density $f(E)g(E)$ shaded green. The white dashed line is E_F; the red line is where the analyser slit is set.
- **Fermi edge, expanded**: the same edge magnified, with the 90% and 10% levels marked and the width between them shaded. This is the measurement you will use.
- **Analyser readout**: temperature, E_F, the slit energy, $f(E)$ at the slit, the detector count rate and $k_B T$.
- **Control panel**: the **Sample** dial (K, Na, Ag, Cu, Al, Si), the **Sample temperature** knob (1–5000 K, logarithmic) and the **Analyser energy** knob. **Park slit on E_F** drives the slit exactly onto the Fermi level.

The Fermi energy is not something you dial in: it is computed from the conduction electron density of whichever sample is loaded, which is why aluminium (three electrons per atom) reads so much higher than potassium.

4.4 Guided Observations

Task: A — The step at absolute zero

Load **copper** and take the sample down to 1 K.

a) Describe the shape of $f(E)$. What is $f(E)$ for $E < E_F$ and for $E > E_F$?

b) Drive the analyser slit slowly across E_F and watch the count rate. Describe what happens.

c) This is the Pauli exclusion principle at work. How many electrons can occupy a single quantum state? _____

Task: B — Heat the electron gas

Keeping copper loaded, take the sample to each temperature below. Press **Park slit on E_F** at each one to check $f(E_F)$, then read the edge width from the expanded display.

Table 4.1: Fermi edge of copper, $E_F \approx 7.0\,\text{eV}$.

T **(K)**	k_BT **(meV)**	$f(E_F)$	**Edge width** W **(meV)**	$k_B = W/4.394T$ **(eV/K)**
1				
300				
1000				
3000				
5000				

Key result: at every temperature, $f(E_F) =$ _____. This is true by definition.

Task: C — Measure Boltzmann's constant

Plot your edge widths W against T. The gradient is $4.394\,k_B$.
Gradient = _____ eV/K k_B = _____ eV/K Accepted: 8.617×10^{-5} eV/K
Percentage difference: _____ %

Task: D — Different metals, and a semiconductor

Set the temperature to 300 K and step through the sample rack.

Sample	n **(m^{-3})**	E_F **(eV)**	k_BT/E_F **(%)**
Potassium			
Sodium			
Silver			
Copper			
Aluminium			

Now load **intrinsic silicon**.

a) Where does E_F sit relative to the gap?
_____

b) Park the slit inside the gap. What does the counter read, and why, given that $f(E)$ there is not zero?

4.5 Analysis Questions

1. The electronic heat capacity of a metal is $C_{\mathrm{el}} = \gamma T$ with $\gamma \propto 1/E_F$. Using the fact that only electrons within $\sim k_B T$ of E_F can be excited, argue why $C_{\mathrm{el}} \propto T/E_F$, and why that is so much smaller than the classical $\frac{3}{2} N k_B$.

2. For copper at room temperature the bench reads $k_B T/E_F$ well under 1%. Explain why the conductivity of a metal therefore changes only slightly with temperature, and say which part of the distribution actually carries the current.

3. Aluminium contributes three electrons per atom rather than one. How does that show up in E_F? Is the effect linear in n?

4. Explain why raising the temperature increases the conductivity of a semiconductor but decreases it in a metal.

Physics Problems

1. Copper has $E_F = 7.04\,\mathrm{eV}$. Calculate the Fermi temperature $T_F = E_F/k_B$ and explain why it shows that quantum statistics dominate even at room temperature.
2. Why can the Maxwell-Boltzmann distribution not be used for electrons in a metal? Which principle forces Fermi-Dirac statistics?
3. Show that the mean kinetic energy of a free electron gas at $T = 0$ is $\bar{E} = \frac{3}{5} E_F$, not zero. Why do the electrons have kinetic energy at absolute zero?
4. From $E_F = \frac{\hbar^2}{2m}(3\pi^2 n)^{2/3}$, work out the electron density that would give $E_F = 5\,\mathrm{eV}$ and compare it with the samples in the rack.

CHAPTER 5

Experiment 5: Electronic Band Structure

Apparatus: Kronig-Penney Band Synthesiser (Bench 5)

Duration: 3 hours
Topics: Bloch theorem, Kronig-Penney model, energy bands, band filling, classification of
Kittel: Chapter 7
Asset tag: MZU-PE / KPS-5

Student Name:		**Date:**	
Student Number:		**Group:**	

5.1 Learning Objectives

Learning Objectives

1. Watch band gaps open as a periodic potential is switched on.
2. Fill the bands with electrons and locate the Fermi level.
3. Classify a solid as metal, semimetal, semiconductor or insulator from its band structure.
4. Test the classification with a conduction measurement.
5. Observe the opposite temperature dependence of a metal and a semiconductor.

5.2 Background Theory

Key Equations

The Kronig-Penney model gives the allowed energies of an electron in a periodic array of barriers of strength P:

$$\cos ka = P\,\frac{\sin \alpha a}{\alpha a} + \cos \alpha a, \qquad \alpha = \frac{\sqrt{2mE}}{\hbar}.$$

Whenever the right-hand side exceeds 1 in magnitude there is no real k: that

range of energies is **forbidden**. Energies are naturally measured in

$$E_0 = \frac{\hbar^2}{2ma^2},$$

which is 0.42 eV for $a = 3$ Å.

Each band holds **two electrons per unit cell**. An odd number of electrons per cell leaves a half-filled band and the solid conducts; an even number fills bands exactly, and conduction then depends entirely on the gap above.

5.3 At the Bench

Bench 5 — Kronig-Penney Band Synthesiser

Open **Bench 5** from the equipment rack.

▶ At the bench

- **Band diagram** (top): E against k in the reduced zone, from $-\pi/a$ to $+\pi/a$. Each allowed band is drawn in its own colour; forbidden gaps are shaded red. The white dashed line is the Fermi level.
- **Conduction test**: a small circuit — a 5 V supply, the specimen, a 1 kΩ resistor and a lamp. The lamp glows in proportion to the current, and the ammeter reads it whether you can see the glow or not.
- **Classification** panel: what the specimen behaves as, the gap at E_F, the Fermi level, and a table of every band edge.
- **Control panel**: the **Barrier strength** P knob, the **Electrons per cell** knob with 1/2/3/4 preset buttons, and **Lattice constant** a and **Temperature** knobs.

5.4 Guided Observations

Task: A — From free electrons to bands

Set $P = 0$ and look at the lowest band — it is the free-electron parabola folded into the zone. Now wind P up in steps and record the first band gap.

P	**Band 1 width (eV)**	**First gap (eV)**	**Band 2 width (eV)**
0			
2			
6			
12			
20			
30			

Question: what happens to the *width* of a band as P increases, and what does that mean for the electrons? _____

Task: B — Filling and classification

Set $P = 6$ and $a = 3\,\text{Å}$. Use the preset buttons to set 1, 2, 3 and 4 electrons per cell in turn.

e^-**/cell**	E_F **(eV)**	**In band or gap?**	**Classification**	**Current (A)**
1				
2				
3				
4				

Question: what is the rule connecting the number of electrons per cell to whether the solid conducts? _____

Task: C — Build a semiconductor and an insulator

With 2 electrons per cell, adjust P (and a if you need to) until the gap at E_F matches a real material.

a) Silicon, $E_g \approx 1.1\,\text{eV}$: P = _____, a = _____ Å, current = _____ A.

b) Diamond, $E_g \approx 5.5\,\text{eV}$: P = _____, a = _____ Å, current = _____ A.

c) Describe the lamp in each case.

_____

Task: D — Temperature dependence

Leave a gap of about 1 eV set and sweep the **Temperature** knob. Then set 1 electron per cell (a metal) and repeat the sweep to fill the right-hand column.

T (K)	Current, 1 eV gap (A)	Current, metal (A)
100		
200		
300		
500		
800		

5.5 Analysis Questions

1. Plot the first band gap against P from Task A. Is the relationship linear? What is happening physically as P increases?

2. The bands flatten as P grows. Since $v_g = \frac{1}{\hbar}\frac{dE}{dk}$, what does a flatter band mean for how easily an electron moves through the crystal?

3. Why does the group velocity go to zero at the zone boundary, whatever the value of P?

4. From Task D, describe how the current changes with temperature for the 1 eV gap and for the metal, and explain the opposite signs.

Physics Problems

1. Show that $E_0 = \hbar^2/2ma^2$ is about 0.42 eV for $a = 3$ Å, and confirm it against the panel.
2. State the difference between an insulator and a semiconductor in terms of band structure alone. Is there a sharp boundary?

3. Intrinsic carrier density goes as $n_i \propto e^{-E_g/2k_BT}$. By what factor does it change between 300 K and 400 K for a 1.1 eV gap? Check against the ammeter.
4. Sodium has one valence electron per cell and is a metal; magnesium has two and is still a metal. Using the band diagram, suggest what must be true of magnesium's bands.
5. Explain the physical meaning of Bloch's theorem, and why k remains a good quantum number in a periodic potential even though momentum is not conserved.

CHAPTER 6

Experiment 6: The *p-n* Junction and Diode Characteristics

Apparatus: Semiconductor Curve Tracer (Bench 6)

Duration: 3 hours
Topics: Depletion region, band bending, rectification, Shockley equation, breakdown
Kittel: Chapter 8
Asset tag: MZU-PE / CVT-6

Student Name:		**Date:**	
Student Number:		**Group:**	

6.1 Learning Objectives

Learning Objectives

1. Record the current-voltage characteristic of a diode with a curve tracer.
2. Relate band bending and depletion width to the applied bias.
3. Extract the ideality factor from a semi-logarithmic plot.
4. Measure how the characteristic shifts with temperature.
5. Compare devices of different band gap, and observe Zener breakdown.

6.2 Background Theory

Key Equations

The Shockley diode equation:

$$I = I_0 \left[\exp\left(\frac{qV}{\eta k_B T} \right) - 1 \right],$$

with η the ideality factor and $k_B T/q$ the thermal voltage, 25.9 mV at 300 K. The saturation current carries the temperature dependence of the minority carriers,

$$I_0 \propto T^3 e^{-E_g/k_B T},$$

which is why the whole characteristic shifts left as the device is warmed. The

depletion region scales as

$$W \propto \sqrt{V_{bi} - V}.$$

6.3 At the Bench

Bench 6 — Semiconductor Curve Tracer

Open **Bench 6** from the equipment rack.

▶ At the bench

- **Curve tracer** (top): the characteristic is drawn as the supply sweeps. **Sweep** runs it, **Clear** wipes the trace, and the **Log I** toggle switches the current axis to a logarithmic scale — essential for the first analysis question. The amber crosshair marks the present operating point.
- **Junction band diagram**: a live view of the bands bending across the junction, with the barrier height annotated and the depletion region marked. Carrier flow arrows appear once forward current flows.
- **Bench meters**: supply voltage, the voltage across the junction itself, the current, the chamber temperature, the thermal voltage and the barrier height.
- **Control panel**: the **Device socket** dial (Ge, Si, GaAs, Zener, Schottky), the **Bias voltage** knob, the **Current limit** R knob, the **Chamber temp** knob, and the sweep **Start** and **Stop** range knobs.

Note

Read the *junction* voltage, not the supply voltage. The difference is the drop across the limiting resistor, and at high current it is most of the reading. This is exactly why a real characteristic is taken with a four-terminal (Kelvin) connection.

6.4 Guided Observations

Task: A — Band bending under bias

Socket the **silicon** diode with a 100 Ω limit resistor at 300 K.

Bias	V junction (V)	Barrier (eV)	W/W_0	Which way do the bands bend?
0				
+0.6 V				
−4 V				

Task: B — Record the characteristic

Press **Sweep** and let the tracer draw the whole curve. Then set the bias by hand and record the current at each point.

Table 6.1: Forward characteristic of the silicon diode at 300 K.

V **junction (V)**	I **(mA)**	$\ln(I/\mathrm{mA})$	**Notes**
0.40			
0.50			
0.55			
0.60			
0.65			
0.70			

Task: C — Temperature dependence

Hold the bias so the junction sits at 0.6 V, and take the chamber from 250 K to 400 K.

T **(K)**	I **at** $V_j = 0.6$ **V (mA)**	**Knee voltage at 1 mA (V)**
250		
275		
300		
325		
350		
400		

Result: the knee moves by _____ mV per kelvin.

Task: D — Compare the devices

Sweep each device at 300 K and record its knee voltage at 1 mA.

Device	E_g **(eV)**	**Knee at 1 mA (V)**	η
Germanium	0.67		
Silicon	1.12		
Gallium arsenide	1.42		
Schottky	0.45		

Finally socket the **Zener**, set the sweep to start at -8 V and run it. Breakdown voltage = _____ V.

6.5 Analysis Questions

1. Switch the tracer to a logarithmic current axis. Using your Task B data, plot $\ln I$ against V over the exponential region. The gradient is $q/\eta k_B T$ — extract η and compare with the panel.

2. Above about 1 mA the log plot stops being straight. Which circuit element causes that, and how could you confirm it experimentally?

3. From Task C, how many millivolts does the knee move per kelvin? Explain the sign using the temperature dependence of I_0.

4. Rank Ge, Si and GaAs by band gap and by knee voltage. Are the two orders the same? Why should they be?

5. Describe what happens to the depletion width and the barrier height in reverse bias, and why that makes the junction a rectifier.

Physics Problems

1. Show that at 300 K the thermal voltage $k_B T/q$ is about 25.9 mV, and confirm it against the panel.
2. A silicon diode passes 1 mA at 0.6 V. Estimate the current at 0.7 V assuming $\eta = 1.6$ and ignoring series resistance. Compare with the tracer.
3. Why is a Zener diode operated deliberately in reverse breakdown, while an ordinary rectifier must never be?
4. Explain why the Schottky diode has η close to 1 while the p-n junctions do not. What does η actually measure?

CHAPTER 7

Experiment 7: The Hall Effect: Identifying Carriers

Apparatus: Hall Probe and Electromagnet (Bench 7)

Duration: 3 hours
Topics: Lorentz force, Hall coefficient, carrier type and concentration, offset removal
Kittel: Chapter 8
Asset tag: MZU-PE / HAL-7

Student Name:		**Date:**	
Student Number:		**Group:**	

7.1 Learning Objectives

Learning Objectives

1. Set up a Hall measurement: constant current, calibrated field, thin sample.
2. Determine the sign of the carriers from the sign of the Hall voltage.
3. Remove the contact misalignment offset by reversing the field.
4. Obtain the carrier concentration from your own measurements.
5. Understand why the effect is so small in a metal.

7.2 Background Theory

Key Equations

Carriers moving through a magnetic field are deflected sideways until the transverse electric field balances the Lorentz force:

$$V_H = \frac{IB}{nqt} = \frac{R_H I B}{t}, \qquad R_H = \frac{1}{nq}.$$

The *sign* of R_H identifies the carrier — negative for electrons, positive for holes. The magnitude gives the concentration:

$$n = \frac{IB}{e\,t\,V_H}.$$

Combining with the resistivity gives the mobility, $\mu = |R_H|/\rho$.

7.3 At the Bench

Bench 7 — Hall Probe and Electromagnet

Open **Bench 7** from the equipment rack.

▶ At the bench

The Hall bar sits between the pole pieces of an electromagnet. Carriers drift along it and are pushed sideways by the Lorentz force; charge piles up on one edge and the nanovoltmeter across the Hall contacts reads the resulting voltage.

- **Hall bar** (top): the field symbols show ⊗ into the page or ⊙ out of it, and their density follows the field strength. Watch which edge the carriers are pushed to, and which sign of charge accumulates there.
- **Bench instruments**: a moving-coil gaussmeter, a moving-coil sample-current meter, and digital readouts for the raw voltmeter reading, the flux density, the sample current, the corrected V_H, the Hall coefficient and the sample thickness.
- **Measure at $\pm B$**: takes a reading at $+B$ and at $-B$ and reports both, their half-sum (the offset) and their half-difference (the true Hall voltage).
- **Control panel**: the **Specimen** dial (n-Ge, p-Ge, n-Si, InSb, Cu), the **Magnet current** knob, **Field direction** and **Current direction** switches, and the **Sample current** knob.

Note

Why reverse the field? The Hall contacts can never be placed exactly opposite one another, so part of the ordinary voltage drop along the bar appears across them. That offset does not care which way the field points, but the Hall voltage does. Half the difference of the readings at $+B$ and $-B$ is therefore the Hall voltage alone. Use **Measure at $\pm B$** before every recorded point.

7.4 Guided Observations

Task: A — Watch the carriers deflect

Load **n-Ge**, set 10 mA and wind the magnet to 3 A.

a) Which edge do the carriers pile up on, and what sign of charge is it?

_____

b) Switch to **p-Ge**. Do the carriers move to the *same* edge or the opposite one? _____

c) What happened to the sign of V_H? _____

d) Reconcile (b) and (c): both carrier types deflect the same way, yet the

voltage reverses. Explain.

_____

Task: B — V_H against B

Load **n-Ge** and hold the sample current at 20 mA.

Magnet (A)	B **(T)**	$V(+B)$ **(mV)**	$V(-B)$ **(mV)**	V_H **(mV)**
0				
1				
2				
4				
6				
8				

Offset from the half-sum: _____ mV. Is it the same at every field?

_____

Task: C — V_H against I

Hold the magnet at 4 A and step the sample current.

I **(mA)**	V_H **(mV)**	R_H **(m^3/C)**	n **(m^{-3})**
5			
10			
20			
35			
50			

Task: D — Metals and thin films

a) Load the **copper** foil at full current and full field. What does the voltmeter show, and why?

_____

b) Copper has $n = 8.5 \times 10^{28}\,\mathrm{m^{-3}}$; the germanium has $10^{21}\,\mathrm{m^{-3}}$. By what factor should V_H differ? _____

c) Load the **InSb** film. It is only 0.15 mm thick. What does that do to V_H, and why are commercial Hall probes made this way?

_____

7.5 Analysis Questions

1. Plot your Task B data as V_H against B. Is it a straight line all the way? If it bends over at high magnet current, is that the sample or the magnet?

2. From the gradient of your Task C plot, V_H against I, extract R_H and then n. Compare with the value the panel reports.

3. Explain why the Hall voltage is so much larger in a semiconductor than in a metal, using the carrier densities on the panel.

4. What would happen to V_H if you reversed both the field and the current at the same time? Try it and explain the result.

Physics Problems

1. A germanium sample 1.0 mm thick carries 20 mA in a field of 0.35 T and gives $V_H = -13.1$ mV. Calculate R_H and n, and state the carrier type.
2. Show that halving the sample thickness doubles the Hall voltage for the same current and field. Why is a good Hall probe always a thin film?
3. Copper has $n = 8.5 \times 10^{28}\ \mathrm{m^{-3}}$. Calculate V_H for a 50 µm foil carrying 50 mA in 0.6 T, and compare with the 0.3 µV resolution of the voltmeter.
4. Combine R_H with the resistivity on the panel to obtain the mobility from $\mu = |R_H|/\rho$, and compare germanium with indium antimonide.

CHAPTER 8

Experiment 8: Semiconductor Band Gaps from LEDs

Apparatus: LED Characterisation Bench (Bench 8)

Duration: 3 hours
Topics: Photon emission, direct band gap, Planck's constant, LED threshold voltage
Kittel: Chapter 8
Asset tag: MZU-PE / LED-8

Student Name:		**Date:**	
Student Number:		**Group:**	

8.1 Learning Objectives

Learning Objectives

1. Measure the turn-on voltage of an LED at a defined current.
2. Relate the emission wavelength to the band gap of the emitting material.
3. Determine Planck's constant from your own measurements, with an uncertainty.
4. Observe how the band gap shifts with temperature.
5. Explain why silicon cannot be used to make an efficient LED.

8.2 Background Theory

Key Equations

An LED emits when an electron in the conduction band recombines with a hole, giving up its energy as a photon:

$$eV_0 \approx E_g = \frac{hc}{\lambda}.$$

Plotting the turn-on voltage V_0 against $1/\lambda$ therefore gives a straight line of gradient hc/e, from which

$$h = \frac{e}{c} \times \text{gradient}.$$

With λ in nm, $hc = 1239.8\,\text{eV nm}$, so the gradient should come out at $1239.8\,\text{V nm}$.

8.3 At the Bench

Bench 8 — LED Characterisation Bench

Open **Bench 8** from the equipment rack.

▶ At the bench

Six LEDs are mounted in a rotating **turret** on an optical bench, facing a spectrometer.

- **Optical bench** (top): the turret and the device on axis, which glows in its own colour when current flows, and the spectrometer head.
- **Spectrometer**: the emission spectrum, with a visible-spectrum strip along the wavelength axis for reference. Readouts give the peak wavelength, the photon energy hc/λ and the band gap.
- **Planck plot**: V_0 against $1/\lambda$, built *from the readings you record*. Once you have two or more points it fits a least-squares line and reports the gradient, the intercept, r^2, and the value of h with its standard error.
- **Bench meters**: supply voltage, the voltage across the LED, the current, the junction temperature, $1/\lambda$ and V_0.
- **Control panel**: the **Turret position** dial, the **Supply voltage** knob, **Auto-set to 1.00 mA**, and the **Series resistor** and **Junction temp** knobs.

Note

Turn-on is not a sharp event — the current rises exponentially — so "V_0" only means something once you fix the current at which you read it. This bench defines it at $1.000\,\textbf{mA}$. Use the fine vernier (hold **Shift**) to sit exactly on that current before you record.

8.4 Guided Observations

Task: A — Band gap and colour

Turn the turret through all six devices at $300\,\text{K}$ and read the spectrometer.

LED	**Material**	**λ peak (nm)**	**hc/λ (eV)**	**E_g readout (eV)**
Infrared				
Red				
Amber				
Green				
Blue				
Violet				

Task: B — Measure the turn-on voltage

For each device, raise the **Supply voltage** slowly until the milliammeter reads exactly **1.000 mA**, then read the voltage *across the LED*. Press **Record reading**: the Planck plot picks the point up automatically.

LED	**λ (nm)**	**$1/\lambda$ (nm^{-1})**	**V_0 at 1 mA (V)**
Infrared			
Red			
Amber			
Green			
Blue			
Violet			

Task: C — Determine Planck's constant

With all six points recorded, read the fit from the Planck plot.

Gradient = _____ V nm Intercept = _____ V r^2 = _____

$h = \dfrac{e}{c} \times \text{gradient} =$ _____ J s Accepted: 6.626×10^{-34} J s

Percentage difference: _____ %

Now repeat the gradient by hand from your own table and confirm the platform's number.

Task: D — Temperature dependence

Fit the **blue** LED, hold it at 1 mA, and change the junction temperature.

T (K)	λ peak (nm)	E_g (eV)
200		
250		
300		
350		
420		

Result: the gap changes by _____ meV per kelvin, and the colour shifts towards the _____.

8.5 Analysis Questions

1. Quote your value of h with its uncertainty from the fit, and the percentage difference from the accepted value. Which single measurement contributed most of the error?

2. Your fitted line has a non-zero intercept. Explain why eV_0 is not exactly E_g, and why the gradient still gives the right h.

3. Silicon has a band gap of 1.12 eV, which would put it in the infrared. Why does silicon nevertheless make a very poor LED?

4. From Task D, describe how the peak wavelength changed as you heated the junction, and what that says about the temperature dependence of the band gap.

5. The green LED has the widest spectral line of the six. Suggest a reason connected to the InGaN alloy it is made from.

Physics Problems

1. Show that a photon of wavelength 660 nm has an energy of 1.88 eV, using $E = hc/\lambda$ and $hc = 1240\,\text{eV nm}$.
2. Explain the difference between a direct and an indirect band gap, and why only direct-gap materials are used for LEDs.
3. An InGaN LED emits at 525 nm. Estimate the band gap, and comment on how the indium fraction would have to change to make it emit blue.
4. Using your gradient, work out hc/e in V nm and compare with the accepted 1239.8 V nm.

CHAPTER 9

Experiment 9: Superconductivity: BCS Theory and the Meissner Effect

Apparatus: Cryostat and Levitation Stage (Bench 9)

Duration: 3 hours
Topics: Meissner effect, BCS energy gap, penetration depth, critical field, type I and type
Kittel: Chapter 10
Asset tag: MZU-PE / CRY-9

Student Name:		**Date:**	
Student Number:		**Group:**	

9.1 Learning Objectives

Learning Objectives

1. Cool a sample through its transition and follow the four-probe resistance to zero.
2. Observe flux expulsion and magnetic levitation.
3. Measure the temperature dependence of the energy gap and the penetration depth.
4. Distinguish type I from type II behaviour by their critical fields.
5. Understand why the choice of coolant decides what can be demonstrated.

9.2 Background Theory

Key Equations

BCS theory pairs electrons through the lattice and opens a gap in the excitation spectrum:

$$2\Delta(0) = 3.53\,k_B T_c, \qquad \frac{\Delta(T)}{\Delta(0)} \simeq \tanh\left(1.74\sqrt{\frac{T_c}{T}-1}\right).$$

The field is screened over the London penetration depth,

$$B(x) = B_0 e^{-x/\lambda_L}, \qquad \frac{\lambda(T)}{\lambda(0)} = \frac{1}{\sqrt{1-(T/T_c)^4}},$$

and superconductivity is destroyed above the critical field

$$H_c(T) = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right].$$

A type I material expels the field completely up to H_c; a type II admits quantised vortices between H_{c1} and H_{c2}.

9.3 At the Bench

Bench 9 — Cryostat and Levitation Stage

Open **Bench 9** from the equipment rack.

▶ At the bench

A superconducting disc sits on a pedestal inside a dewar, with a small permanent magnet above it.

- **Levitation stage** (top, 3D — drag to orbit): the field lines bow around the disc once it is superconducting, and the magnet lifts off. In the mixed state you can see the flux vortices threading the disc.
- **Four-probe resistance**: R against T, with the transition and the coolant base temperature marked and a cursor at your working point.
- **BCS energy gap** and **Critical field**: $\Delta(T)/\Delta(0)$ against T/T_c, and H_c (or H_{c1} and H_{c2}) against T/T_c with your applied field marked.
- **Bench readings**: thermometer, resistance, applied field, T/T_c, $\lambda(T)/\lambda(0)$ and the levitation height.
- **Control panel**: the **Specimen** dial (Al, Pb, Nb, Nb_3Sn, YBCO, BSCCO), the **Coolant** dial, the **Setpoint** knob, **Cool to base**, and the **Magnet field** knob.

Note

The cryostat cannot go below the boiling point of what is in the dewar. Liquid nitrogen stops at 77 K, liquid helium at 4.2 K, and pumped helium at about 1.1 K. Dial a setpoint below the base and the instrument will hold at the base and tell you so.

9.4 Guided Observations

Task: A — The Meissner effect

Load **YBCO**, put **liquid nitrogen** in the dewar, and set the magnet to about 10 mT. Cool from 300 K down to 77 K.

a) At what temperature does the resistance reach zero? $T_c =$ _____ K

b) Describe what the field lines do as you pass through T_c.

_____

c) Record the levitation height at 77 K: _____ mm. Warm slowly back through T_c and describe how it changes.

_____

Task: B — The energy gap

Stay on YBCO and step the setpoint so that T/T_c takes the values below.

T/T_c	T **(K)**	$\Delta(T)$ **(meV)**	$\Delta(T)/\Delta(0)$	$\lambda(T)/\lambda(0)$
0.10				
0.30				
0.50				
0.70				
0.90				
0.98				

Task: C — Type I against type II

Switch the dewar to **liquid helium**.

a) Load **lead** (type I) and cool to 4.2 K. Raise the field until the resistance returns. $H_c =$ _____ T. Compare with $H_c(0)[1-(T/T_c)^2]$ using $H_c(0) = 80.3$ mT: _____ T.

b) Load **niobium** (type II) and cool to 4.2 K. Raise the field slowly. At what field do vortices first appear, i.e. the state lamp changes? $H_{c1} =$ _____ T. At what field does the resistance return? $H_{c2} =$ _____ T.

c) Describe the difference between what you saw for lead and for niobium.

_____

Task: D — Why liquid nitrogen is not enough

Put **liquid nitrogen** back in the dewar, press **Cool to base**, and try each specimen in turn at a small field.

Specimen	T_c (K)	T reached (K)	Superconducting?
BSCCO			
YBCO			
Nb_3Sn			
Nb			
Pb			
Al			

Question: where is the dividing line, and what does it cost to cross it?

9.5 Analysis Questions

1. Why does the BCS energy gap close at T_c? What happens to the Cooper pairs there?

2. From your Task B data, plot $\lambda(T)/\lambda(0)$ against T/T_c. Why does the penetration depth diverge as $T \to T_c$, and what does that mean for the screening currents?

3. State the difference between a perfect conductor and a superconductor. Which of the two effects you observed could a perfect conductor *not* reproduce?

4. From Task D, explain exactly why liquid nitrogen works for YBCO and BSCCO but not for niobium, lead or aluminium.

5. The levitation height follows the superfluid density $1-(T/T_c)^4$. Explain why the magnet sinks as the disc warms even before the resistance returns.

Physics Problems

1. Using $2\Delta(0) = 3.53 k_B T_c$, calculate the zero-temperature gap of niobium in meV and compare with the panel.
2. Explain how the isotope effect, $T_c \propto M^{-1/2}$, points to phonons as the pairing mechanism.
3. A lead sample is at 4.2 K. Using $H_c(T) = H_c(0)[1 - (T/T_c)^2]$ with $H_c(0) = 80.3\,\mathrm{mT}$, calculate the field that would drive it normal, then check it on the bench.
4. Why can a type II superconductor carry current in a very high field while a type I cannot? Refer to flux vortices and to pinning.

CHAPTER 10

Experiment 10: Electrical and Thermal Properties of Metals

Apparatus: Four-Point Probe and Thermal Bench (Bench 10)

Duration: 3 hours
Topics: Resistivity, Matthiessen's rule, Bloch-Grüneisen, thermal conductivity, Wiedeman
Kittel: Chapter 6
Asset tag: MZU-PE / FPP-10

Student Name:		**Date:**	
Student Number:		**Group:**	

10.1 Learning Objectives

Learning Objectives

1. Measure resistivity with a four-point probe, and understand why four probes are needed.
2. Separate the residual and phonon contributions to the resistivity.
3. Measure thermal conductivity from a heat flow and a temperature difference.
4. Test the Wiedemann-Franz law and interpret departures from it.
5. Explain why a disordered alloy behaves so differently from a pure metal.

10.2 Background Theory

Key Equations

Matthiessen's rule:

$$\rho(T) = \rho_{\text{res}} + \rho_{\text{ph}}(T).$$

The residual term is impurity and defect scattering and is independent of temperature. The phonon term follows the Bloch-Grüneisen form, $\rho_{\text{ph}} \propto T^5$ well below Θ_D and $\propto T$ well above it.

Wiedemann-Franz law:

$$\frac{\kappa}{\sigma T} = L_0 = 2.44 \times 10^{-8}\ \mathrm{W\,\Omega\,K^{-2}},$$

which holds when the same electrons carry both charge and heat and are scattered the same way. Any extra heat carried by phonons pushes the measured L above L_0.

The four-point probe gives $\rho = \dfrac{V}{I} \cdot \dfrac{A}{s}$; the thermal bar gives $\kappa = \dfrac{PL}{A\,\Delta T}$.

10.3 At the Bench

Bench 10 — Four-Point Probe and Thermal Bench

Open **Bench 10** from the equipment rack.

▶ At the bench

A metal rod of 2×2 mm section sits in a holder inside a furnace/cryostat. Current enters through clamps at the two ends; two probes 20 mm apart measure the voltage. A heater at one end and a heat sink at the other set up a thermal gradient along the same rod.

- **Probe rig** (top): the rod, the four probes, the heater and the heat sink, with the measured probe voltage, resistivity, gradient and thermal conductivity underneath.
- **Resistivity against temperature**: $\rho(T)$ with the Debye temperature marked. When cold work has been applied, the undamaged curve is drawn dashed for comparison — Matthiessen's rule made visible.
- **Thermal conductivity** and **Lorenz number** screens, the latter with L_0 drawn as a dashed reference.
- **Room-temperature comparison**: a logarithmic bar chart of every rod in the rack.
- **Control panel**: the **Specimen rod** dial, the **Rod temperature** knob, the **Probe current** and **Cold work** knobs, and the **Heater power** knob with its switch.

Note

Why four probes? A two-terminal measurement includes the resistance of the leads and the contacts, which on a good metal is far larger than the sample itself. Passing the current through the outer pair and measuring the voltage with the inner pair means no current flows in the voltage leads, so their resistance does not matter.

10.4 Guided Observations

Task: A — ρ against T

Load **copper** with no cold work and set the probe current to 100 mA.

Table 10.1: Resistivity of copper, four-point probe, $s = 20\,\text{mm}$, $A = 4\,\text{mm}^2$.

T (K)	V probe (μV)	ρ (nΩ m)	κ (W m^{-1}K^{-1})
20			
40			
77			
150			
300			
500			
700			
900			

Task: B — Compare the rods

At 300 K, record the resistivity of every rod in the rack.

Rod	ρ at 300 K (nΩ m)	κ (W m^{-1}K^{-1})	Rank
Silver			
Copper			
Gold			
Aluminium			
Tungsten			
Nickel			
Iron			
Nichrome			

Task: C — Test Wiedemann-Franz

For copper, silver and nichrome at 300 K, switch the heater on, record everything, and work out the Lorenz number.

Rod	ρ (nΩm)	P (W)	ΔT (K)	κ (W/mK)	$L = \kappa\rho/T$
Copper					
Silver					
Nichrome					

Compare each with $L_0 = 2.44 \times 10^{-8}\,\mathrm{W\,\Omega\,K^{-2}}$. Which departs most, and in which direction? _____

Task: D — Matthiessen's rule

Load **copper** and wind the **Cold work** knob up in steps, reading the resistivity at both 20 K and 300 K each time.

Cold work (nΩm)	ρ at 20 K	ρ at 300 K	Residual resistance ratio
0			
10			
20			
40			

a) Does the *slope* of $\rho(T)$ at high temperature change? _____

b) Now repeat on **nichrome**. Why does the same amount of cold work make almost no difference there?

_____

10.5 Analysis Questions

1. From your Task A data, plot ρ against T above Θ_D. Is it linear? Now plot $\log\rho$ against $\log T$ below 40 K and find the exponent. What does Bloch-Grüneisen theory predict?

2. Silver is a better conductor than copper at 300 K, yet copper is used for wiring. Explain the physics of the difference, and then the engineering of the choice.

3. Nichrome barely changes resistivity when heated. Explain that in terms of Matthiessen's rule and the disorder in a substitutional alloy.

4. For the pure metals your measured L should sit close to L_0; for nichrome it comes out higher. Which heat carrier is responsible for the excess?

5. The residual resistance ratio is used industrially as a purity specification for copper. Explain why, and what cold working does to it.

Physics Problems

1. A copper rod of cross-section $4\,\mathrm{mm}^2$ carries $100\,\mathrm{mA}$ and gives $5.0\,\mu\mathrm{V}$ across probes $20\,\mathrm{mm}$ apart. Calculate ρ, then check it against the bench.
2. Use $\kappa = L_0 T/\rho$ to predict the thermal conductivity of copper at $300\,\mathrm{K}$ and compare with the measured value. Where does the difference come from?
3. Explain why metals feel colder than wood at the same temperature, using the thermal conductivities you measured.
4. Why does the thermal conductivity of a pure metal rise to a peak at low temperature and then fall again? Consider each term in Matthiessen's rule in turn.

APPENDIX A

Quick Reference

A.1 Bench index

Bench	Experiment	Apparatus	Kittel
1	Crystal structures	Crystallographic model stage	Ch. 1
2	Bragg diffraction	θ–2θ powder diffractometer	Ch. 2
3	Phonons and heat capacity	Lattice rig and calorimeter	Ch. 4, 5
4	Fermi-Dirac statistics	Electron energy analyser	Ch. 6
5	Band structure	Kronig-Penney synthesiser	Ch. 7
6	The p-n junction	Semiconductor curve tracer	Ch. 8
7	The Hall effect	Hall probe and electromagnet	Ch. 8
8	LED band gaps	LED characterisation bench	Ch. 8
9	Superconductivity	Cryostat and levitation stage	Ch. 10
10	Metal transport properties	Four-point probe and thermal bench	Ch. 6

A.2 Physical constants used in this manual

Quantity	Symbol	Value
Planck constant	h	$6.62607015 \times 10^{-34}\,\mathrm{J\,s}$
Reduced Planck constant	$\hbar$	$1.054571817 \times 10^{-34}\,\mathrm{J\,s}$
Elementary charge	e	$1.602176634 \times 10^{-19}\,\mathrm{C}$
Electron mass	m_e	$9.1093837 \times 10^{-31}\,\mathrm{kg}$
Boltzmann constant	k_B	$1.380649 \times 10^{-23}\,\mathrm{J\,K^{-1}}$
		$= 8.617 \times 10^{-5}\,\mathrm{eV\,K^{-1}}$
Avogadro constant	N_A	$6.02214076 \times 10^{23}\,\mathrm{mol^{-1}}$
Gas constant	R	$8.31446\,\mathrm{J\,mol^{-1}K^{-1}}$
Speed of light	c	$2.99792458 \times 10^{8}\,\mathrm{m\,s^{-1}}$
Lorenz number	L_0	$2.44 \times 10^{-8}\,\mathrm{W\,\Omega\,K^{-2}}$
Convenient product	hc	$1239.8\,\mathrm{eV\,nm}$
Thermal voltage at 300 K	k_BT/q	$25.9\,\mathrm{mV}$
Classical heat capacity	$3R$	$24.94\,\mathrm{J\,mol^{-1}K^{-1}}$

A.3 Control summary

Action	How
Coarse adjustment	Drag a knob up or right, or drag a fader along its slot.
Fine adjustment	Hold **Shift** while dragging, or focus the control and use the arrow keys.
Jump to an extreme	Focus a knob and press **Home** or **End**.
Change a discrete setting	Click a legend on a rotary selector, or use the arrow keys.
Record a measurement	**Record reading** on the notebook panel at that bench.
Export your data	**CSV** on the bench notebook, or **Export everything** on the Lab Notebook page.
Change the lighting	Three-position switch, top right of every page.
Mute the bench	Speaker button, top right.